

**Optimizing Pressure in Compressive Textiles and
Utilizing Smart Sensors to Monitor Patient Recovery**

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Abstract

This study was designed to examine how to better monitor patients throughout compression therapy. Compressive wraps are used to optimize blood flow in patients in order to encourage proper healing and decrease the likelihood of medical complications. The pressure being applied by the wrap determines its effectiveness, so it would be ideal if this could be monitored real-time. New advancements in smart sensors may allow for this to occur. Until then, it would be useful to have tables of elongation versus pressure, so that doctors and nurses have a reference that can be used to estimate the pressure being applied to the wound. Temperature and moisture sensing were also considered, since they could be used to monitor patient temperature and potentially sense fluid build-up. Skin temperature sensing was found to be possible using the SensorPush Temperature and Humidity Sensor. A table has been fabricated using tensile test data that shows the acceptable range of percent elongations for each tested compressive wrap. It was determined that stress relaxation is prevalent in compressive wraps, and this must be taken into consideration in future testing.

Introduction

Medical wraps are used in compression therapy in order to apply a constant pressure to a wound or surgical site. Compression therapy is the use of these wraps to apply pressure to a wound after the patient has had surgery—typically on the legs, flank, or stomach [1], [2].

Doctors often prescribe compressive wraps to patients in order to promote faster healing and reduce the chance of recurrences [1]. Compression therapy wraps vary depending on the part of the body on which they are being applied, but the concept remains the same: pressure must be constantly applied to the site of the wound in order to ensure correct healing. The idea of monitoring the patient's vitals, temperature, activity, and sweat rate, in addition to the pressure that the wrap is applying, gives doctors and patients the ability to better monitor the patient's recovery after surgery.

Sensors embedded into fibers have been used in the medical field to some extent. For example, sensor systems have been created to monitor glucose levels in diabetic patients [3]. Diabetes is an example of a condition which greatly benefits from continuous monitoring, and sensors allow doctors to achieve this. Monitoring of glucose level is specific to diabetic patients; however, there are many properties that can be useful no matter what is being treated/monitored. Humidity and respiratory sensors have been built into wearable textiles in order to monitor the patient closely during an MRI [4]. The problem with this type of monitoring is the rigidity of the sensors; a compressive wrap would require a more flexible sensor system. Since they were designed for use on a patient who have been anesthetized and therefore not moving, for these sensors to be used in compressive wraps, the sensors must be made more durable and flexible. Stretchable fiber sensors have also been made for determining pressure in compressive textiles. It is known that the pressure needed for compression therapy is not the same from patient to

patient—the range of 30-50 mmHg is commonly used [5]. It has been shown that it is possible to use an optical sensor to display the strain of the compressive textile [5]. The optical sensor here could prove very useful in future medical wraps, but it would need further testing to determine durability and strength. Alone, the pressure sensor is helpful; however, in order to fully monitor a patient recovering from liposuction or other surgeries requiring compressive wraps, more sensors are needed. Stretchable PDMS sensors have been designed in order to provide a stretchable and flexible strain sensor for use on humans. A dye-doped PDMS optical fiber-based sensor has been designed which shows strong enough mechanical properties to withstand human motion [6]. Optical Fiber Bragg Grating (FBG) sensors have been used in order to monitor curvature, which could be used to observe human motion and activity [7]. FBG has also been used as a means to measure temperature, which could prove useful in the design of compressive textiles [8].

The goal of this project is to determine a method of estimating the amount of pressure being applied to the wound and to explore the viability of sensors in monitoring of the patient during compression therapy.

Literature Review

Compression therapy is commonly employed to ensure proper healing in an optimal time after surgery. After a patient gets out of surgery, the affected body part is wrapped in a somewhat thick, but stretchable, piece of fabric. The most common areas that compression therapy is employed are the legs, stomach, or flanks [1], [2]. Compressive wraps are utilized in order to reduce swelling and fluid accumulation and to allow the wound to heal quicker due to optimal pressure and smoother blood flow [1]. The purpose of compression therapy is that a wrap is tightly placed on an injured part of the body and pressure is constantly applied in order to reduce swelling and induce healing.

Monitoring patients during compression therapy in order to make sure that the wrap is not exerting a non-optimal amount of pressure is not common. Using smart textiles, continuous monitoring can be accomplished. The pressure range that compressive wraps apply is known to be 30—50 mmHg, but the exact optimal pressure differs from patient to patient [5]. Recent advances in smart textiles, fabrics with integrated technology, allows for the integration of sensors into wearable textiles. The integrated sensors can be employed to monitor various vital signs, GPS location, or activity [6], [7]. These materials have been employed in the sports industry, but there are valuable applications to be sought out in the medical field by utilizing smart textile systems [9]. Strain sensors for pressure determination have been realized, but more testing is needed on these textile systems to determine the strength and durability of the wearable compressive wrap [5]. In order to monitor the patient to the full extent, strain sensors need to be combined with various other non-intrusive sensors to determine vital signs, sweat rate, and curvature/activity into one smart compressive wrap.

One popular method of reporting the results from the sensors in smart textiles is using optical cues. J. D. Sandt et. al. created a strain-sensing compressive wrap that is capable of relaying the current pressure on a colorimetric scale [5]. The colors of select fibers in the wrap change with changes in strain, allowing for medical professionals and the patients themselves to detect large changes in pressure, which may call for the adjustment of the compressive wrap. Similarly, J. Guo et. al. developed a novel way to use optical strain sensing to detect motion [5]. The requirement of high flexibility and stretchability were recognized, and a dye-doped PDMS optical fiber was developed. Unlike J. D. Sandt et. al., J. Guo et. al. does perform strength/durability tests on the fabricated smart textile, including tensile tests for strength determination and cyclic loading to determine stretchability and durability. These advancements

allow for doctors to closely monitor pressure applied by the compressive wrap without fear of device failure.

PDMS films can be used to measure more than just strain. H. Jin et. al. developed a stretchable dual-capacitor multi-sensor which is capable of detecting touch, curvature, pressure, and strain [9]. The sensor is comprised of three silver nanowire (AgNW) electrodes with a PDMS coating between each electrode and as a protective layer on the top of the last electrode. The authors seek to correct a problem past researchers have had in that they add directionality into the detection of stimuli. Adding additional measurements to the sensor other than strain adds greatly to its usefulness in medical textiles.

Other than PDMS sensors, hydrogel optical fibers have also been used for strain measurement. J. Guo et. al. developed a highly stretchable and tough hydrogel optical fiber sensor which is capable of stretching to 700% [10]. Dye-doping the hydrogel fiber allows for an optical response to strain which the wearer of the textile could see. Mechanical testing was performed to determine the strength and durability of the fiber sensor, but more cyclic loading tests need to be done to see if the sensor would hold up under the amount of strain it would undergo if it was used in a compressive wrap.

In addition to PDMS and Hydrogel strain sensors, Optical Fiber Bragg Grating (FBG) has been used by F. Urban et. al. to quantify pressure [7]. F. Urban et. al. had the goal of determining whether FBG could be used for a sensor with increased sensitivity and accuracy when compared to the cheaper alternatives. A novel method of using FBG laterally was employed versus the traditionally longitudinal FBG. A pressure capsule was fabricated which included a primary and secondary FBG sensor. The primary FBG sensor was used for pressure determination while the secondary FBG sensor was used for temperature monitoring. This secondary FBG was used for

testing purposes only and does not have an effect on the functionality of the pressure capsule itself, but it still has potential applications when measurements beyond just pressure sensing are needed.

Smart textile systems have been used in the medical field to some extent. One particularly important application is the monitoring of patients under anesthesia—particularly during an MRI. Due to the possible problems that arise during anesthesia, it is safer if patients are monitored throughout the process [3]. J. D. Jonckheere et. al. use optical fiber sensors in order to eliminate the noise that would show up in the MRI reading as well as to remedy the burning of the patient's skin which may occur if conductive fibers/metallic components are used in the fabrication of the sensors.

The goal of our project is to examine ways at which patients can be monitored while participating in compression therapy. This involves determining when the wrap is exerting an optimal amount of pressure as well as considering temperature and humidity sensors as another way to monitor patients. Compressive wraps have been used for many years in the medical field for therapy after surgery, and with the introduction of smart sensors, there is potential to allow patients the ability to recognize when adjustment of the wrap is necessary to ensure optimal healing.

Materials and Methods

Materials Selection and Preparation

Five materials involved in the compression therapy process were analyzed in this study: three commercially available compressive/sports wraps used for compression therapy, one gauze, and an elastic cord used for securing the non-self-adhering types of compressive wraps. The wraps studied were Powerflex Self-Adhering Sports Wrap, Equate Self-Adhering Sports Wrap, and Mueller All-Purpose Support Wrap. The Powerflex Self-Adhering Sports Wrap and Mueller All-Purpose Support Wrap had widths of 3 inches, as compared to the Equate Self-Adhering Sports Wrap with a width of 4 inches. All three were deemed wide enough to incorporate multiple sensors. Band-Aid Johnson & Johnson Large Rolled Gauze had a width of three inches and was analyzed as another type of compressive textile. The last material to be tested was a Woven Non-Roll Elastic cord having a width of 0.75 inches.

The sensors chosen to perform the various functions included the SensorPush Humidity and Temperature Smart Sensor [12], StretchSense Fabric Stretch Sensor [13] and StretchSense Compression Element [14]. The SensorPush sensor was chosen due to its accuracy of $\pm 3^{\circ}\text{C}$ and for its low cost. This sensor transmits the temperature and humidity data via Bluetooth to a smart phone application [12]. The sensor was placed directly on the skin underneath the first layer of compressive wrap. The StretchSense Fabric Stretch Sensor can determine the amount of strain the compressive wrap is experiencing while being used [13]. This is complimented by the StretchSense Compression Element which measures deformation—it can be used to measure forces between the wearer and the compressive wrap [14]. These sensors send real time information to the wearer's smartphone. This gives the wearer the ability to visually see if the compressive wrap is applying too much or too little pressure and quickly relay the information to

doctors. The StretchSense sensors were selected due to their high flexibility and capability to be easily integrated into the fabric compressive wrap through heat-pressing [12].

Due to monetary and time constraints, the StretchSense sensors were not able to be used in this study. Recommendations were made for future work on this topic and included what would have been done had the materials been acquired (see **Future Work**). One SensorPush sensor was purchased and used in the testing of all samples.

Mechanical Testing

Before integration of any sensors, the compressive wraps were tested using an Instron Tensile Tester with a load cell of 5 kN. Samples of the wraps were cut into 1” by 6” rectangular strips. Six samples were tested for each compressive wrap. A gauge length of 3” was used throughout the trials. The test method considered a load drop of 50% as the termination condition, while load and extension were recorded throughout the test. Load was used to determine tensile properties including yield strength and ultimate tensile strength. Load and extension before failure were also recorded.

During the time that the compressive wrap is being used, the material begins to relax. Stress relaxation in materials can be quite consequential to the amount of pressure being applied, so stress relaxation tests were run on all five materials. One test was done per material due to time restraints. All test specimens were prepared in the aforementioned way. The samples were pre-loaded to 30% peak load and held there for 20 minutes. Time started when the pre-loaded was complete, and time was recorded in seconds.

Pressure Determination

Utilizing the load data collected in the tensile tests, the pressure being applied by the compressive wrap can be determined. The collected Extension data was converted to percent

elongation using the known gauge length of 3 inches. Using the table of percent elongation versus load created from this data, pressure can be calculated for each percent elongation, since the area of the test sample was known to be 3 in² [eq. (1)].

$$Pressure = \frac{Load}{Area} \quad (1)$$

These calculated pressures correspond to percent elongations. This allows for the estimation of the range of percent elongation that will exhibit optimal amounts of exerted pressure (30 to 50 mmHg) [5].

Temperature Sensing

The compressive wrap with the SensorPush sensor was tested for ability to measure skin temperature. The temperature sensing accuracy was determined by averaging the results from three trials using the Powerflex Self-Adhering Sports Wrap as the compressive wrap. The trials were performed three hours apart. The SensorPush sensor was placed flat in direct contact with the patient's skin (Figure 1) and the sports wrap was wrapped around and secured to itself (self-adhesion). All trials used a 12-inch sample of the wrap. These values were compared to an average skin temperature in humans of approximately 91.4°F [15]. The room temperature was 73°F for all three trials.



Figure 1. Location of the sensor on the right arm

Results

Mechanical Testing

Percent elongation versus load data for six specimens of each sample compressive wrap were found using an Instron tensile tester. Average max load and the elongation (%) at that load for each sample were noted (Table 1). Utilizing eq. 1, average curves for the percent elongation versus pressure were found for each sample using non-linear regression in Excel (**Appendix I**). Using the data from the average curves, there is a predictable range of elongations that would result in a pressure in the acceptable range of 30 to 50 mmHg (Table 2).

Table 1. Average max load and average elongation at max load for each of the samples

Sample ID	Max Load (lbf)	Elongation at Max Load (%)
Powerflex Self-Adhering Sports Wrap	18.14	219.17
Equate Self-Adhering Sports Wrap	13.49	236.67
Mueller All-Purpose Support Wrap	77.31	302.33
Band-Aid Johnson & Johnson Large Rolled Gauze	8.59	80.67
Woven Non-Roll Elastic Cord	96.29	271.39

Table 2. Acceptable percent elongations at which the pressure is within 30 to 50 mmHg.

Sample ID	Acceptable Range (% Elongation)
Powerflex Self-Adhering Sports Wrap	170-175
Equate Self-Adhering Sports Wrap	155-165
Mueller All-Purpose Support Wrap	120-160
Band-Aid Johnson & Johnson Large Rolled Gauze	35-40
Woven Non-Roll Elastic Cord	25-40

Stress relaxation data was compiled for each of the six samples (**Appendix II**) and analyzed to determine which of the samples had the highest drop in load before stabilizing. Load drop and percentage decrease in load was considered when determining if stress relaxation will have a large impact on the pressure exerted by the wrap (Table 3).

Table 3. Load decrease over the 20-minute stress relaxation tests

Sample ID	Drop in Load (lbf)	Percent Drop in Load (%)
Powerflex Self-Adhering Sports Wrap	2.88	52.87
Equate Self-Adhering Sports Wrap	2.34	57.69
Mueller All-Purpose Support Wrap	17.98	77.52
Band-Aid Johnson & Johnson Large Rolled Gauze	2.00	77.52
Woven Non-Roll Elastic Cord	9.92	34.32

Temperature Sensing

Temperature was determined using a thermometer and the SensorPush sensor. This data was compiled, and percent error was determined (Table 4).

Table 4. Temperature sensed by the SensorPush sensor

Powerflex Self-Adhering Sports Wrap	SensorPush Temperature (°F)
Trial 1	91.5
Trial 2	91.7
Trial 3	91.2
Average	91.5

Discussion

Pressure Determination

By utilizing the average curves found in Appendix I, one can estimate the pressure being applied at different percent elongations. Using Table 2, it can be seen that the Mueller All-Purpose Support Wrap has the largest range, while the Powerflex Self-Adhering Sports Wrap and Band-Aid Johnson & Johnson Large Rolled Gauze are limited to only about five percent. This could prove useful for doctor's when putting the wrap on a patient. If it is determined that a pressure outside of this range is needed, the percent elongation for a particular pressure can be found using the average curves found in **Appendix I**.

The stress relaxation data found in **Appendix II** shows that there is substantial load drop after the initial stretching. The elastic cord has the lowest drop in load, but it is not a compressive wrap itself. The Mueller All-Purpose Support Wrap and Band-Aid Johnson & Johnson Large Rolled Gauze both drop substantially, both decreasing in load by 77.52% after 20 minutes.

Temperature Sensing

Assuming the resting skin temperature of a human is 92.4°F, the SensorPush sensor percent error was .11%. This shows that there is some accuracy to the sensor, when it is used to determine the temperature of forearm skin. A possible point of error could include that the reference skin temperature was for a particular room temperature. The reference temperature was in Celsius (33°C), so the conversion to 92.4°F could produce some error in that some precision is lost when doing measurements in Celsius.

Future Works

Pressure Determination

From Table 3, it can be seen that the stress relaxation of the material has a substantial impact on the actual load applied by the compressive wrap after even a short period of time. Thus, the results showing acceptable range of percent elongation (Table 2) might not be completely accurate of the actual ranges if the wrap is going to be applied for extended periods of time. More testing would need to be done to see if these values are reliable as well as to account for the stress relaxation.

Ideally, there would be no need for these tables showing acceptable range; pressure has the potential to be monitored real-time using sensors such as those mentioned above [13], [14]. Testing needs to be done with these sensors to determine if they are reliable. StretchSense sensors can be both stitched or heat-pressed onto fabrics, therefore allowing them to have applications in both woven and nonwoven materials. Testing to ensure the reliability of the sensors in both woven and nonwoven materials needs to be performed. Examining the durability of these sensors is an important step when determining their viability. Mechanical testing similar to that which was utilized in this study could be used to gain more insight into the abilities of

these sensors. If these sensors prove accurate, they would allow better monitoring of the patients, since they can track the amount of pressure applied throughout the recovery process. Using stress relaxation data, this can be predicted, but outside factors may prove the predictions incorrect.

Humidity Sensing

The next test would be to determine if the SensorPush sensor could detect moisture. A test was designed but was not completed due to time constraint; this would be the next step moving forward. Five trials were to be performed, and the success of each trial noted. In preparation for each trial, the humidity at a dry point on a wooden board should be recorded. Five drops of water were to be placed using a medicine dropper onto the same point of the wooden board. The sensor would need to be immediately moved to the site where the water was dropped, and the humidity monitored for five minutes. The highest peak in humidity during this time would be compared to that of the humidity before the test begun. If the humidity increases sharply when the water is applied, it could be suggested that the SensorPush sensor is able to detect moisture.

Temperature Sensing

To better test the accuracy of the SensorPush sensor's temperature sensing, an accurate skin thermometer could be employed to better determine the deviation from the actual temperature. The accuracy of the sensor could depend on the amount of pressure the wrap is exerting; more testing would need to be done to see if the sensor becomes more accurate/less accurate depending on the amount of pressure. It could be useful to know if being secured by the Woven Non-Roll Elastic has an impact on the accuracy of the temperature sensor.

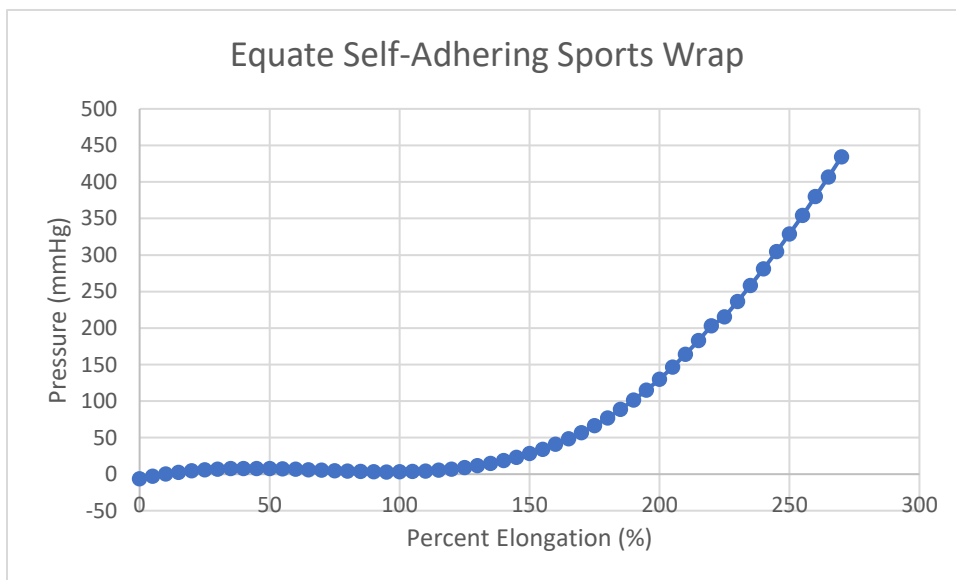
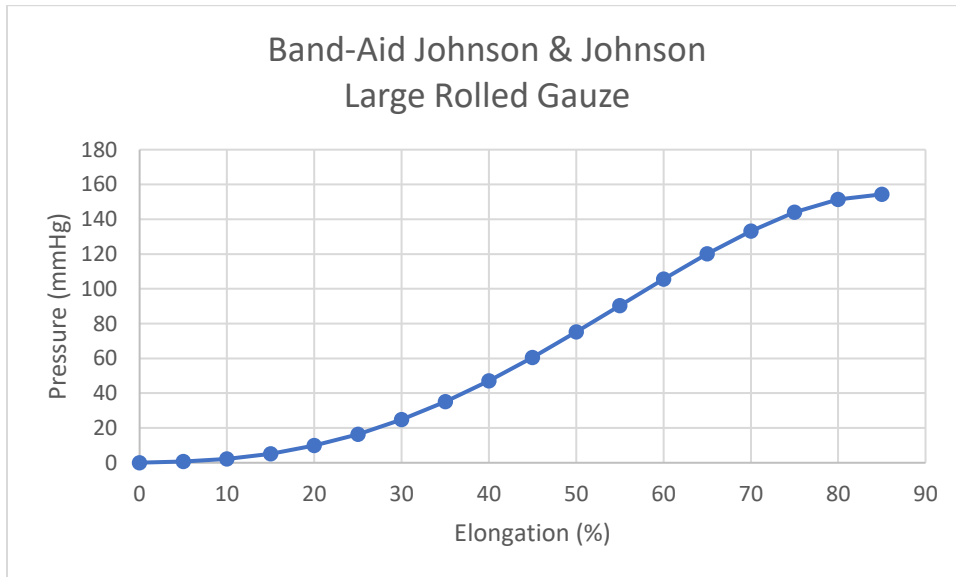
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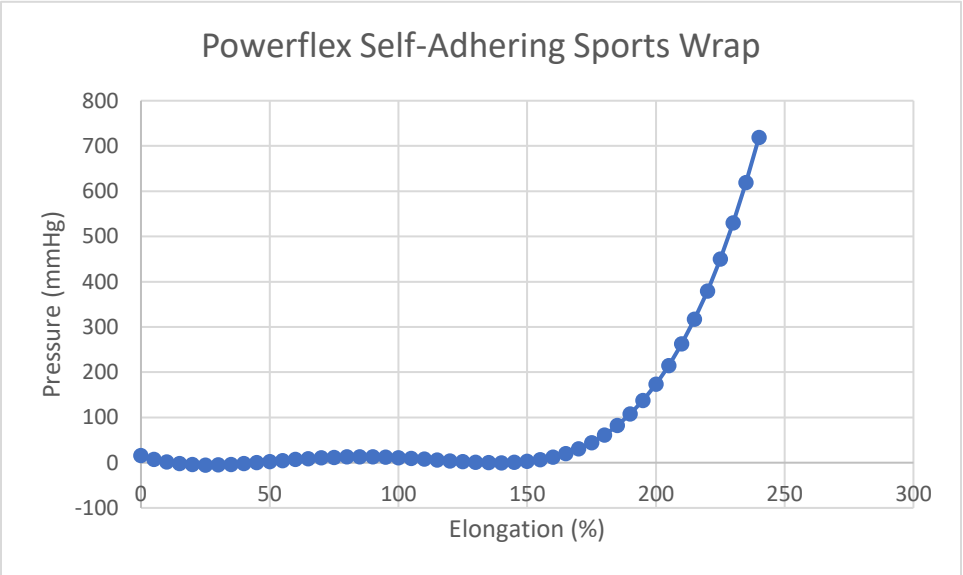
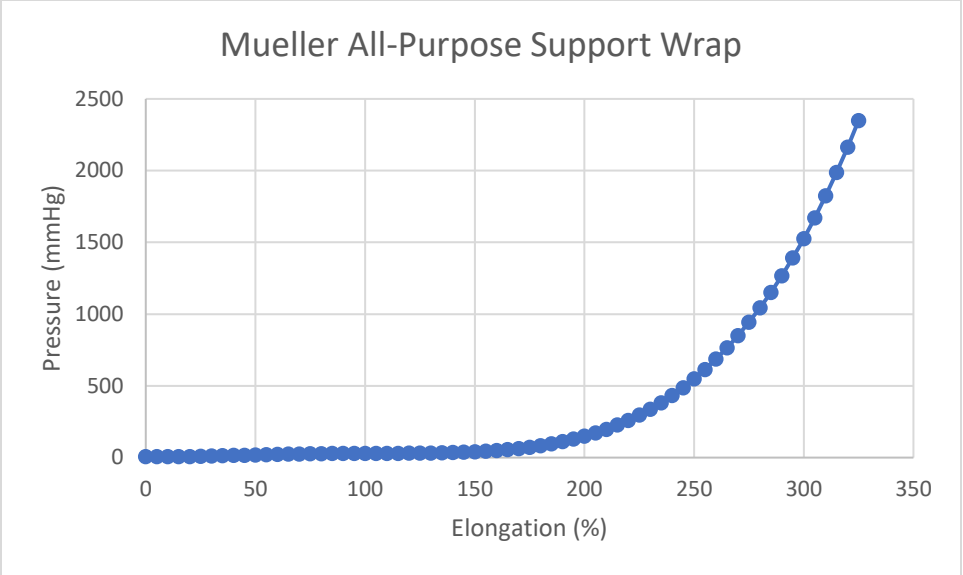
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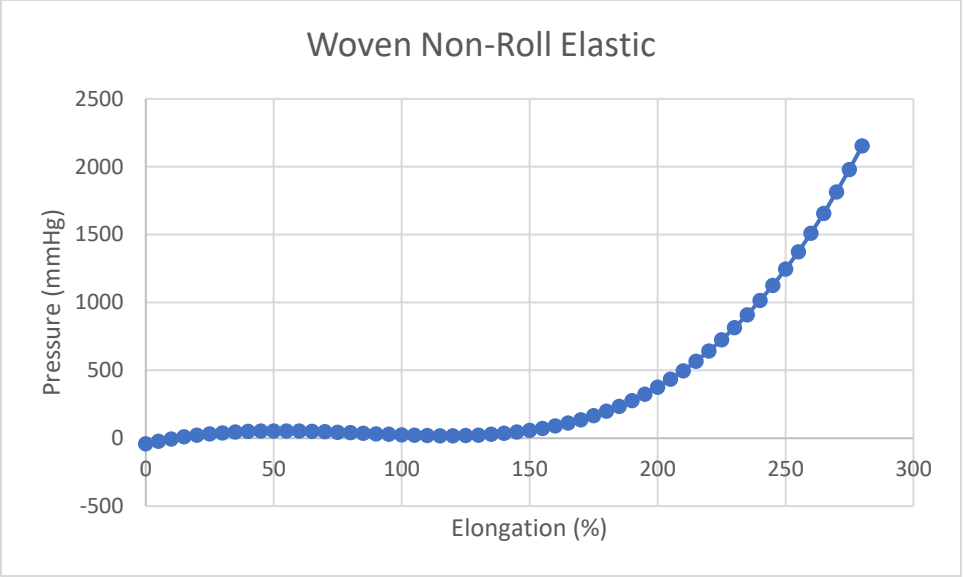
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Appendices

Appendix I. Average curve for each sample illustrating percent elongation versus pressure

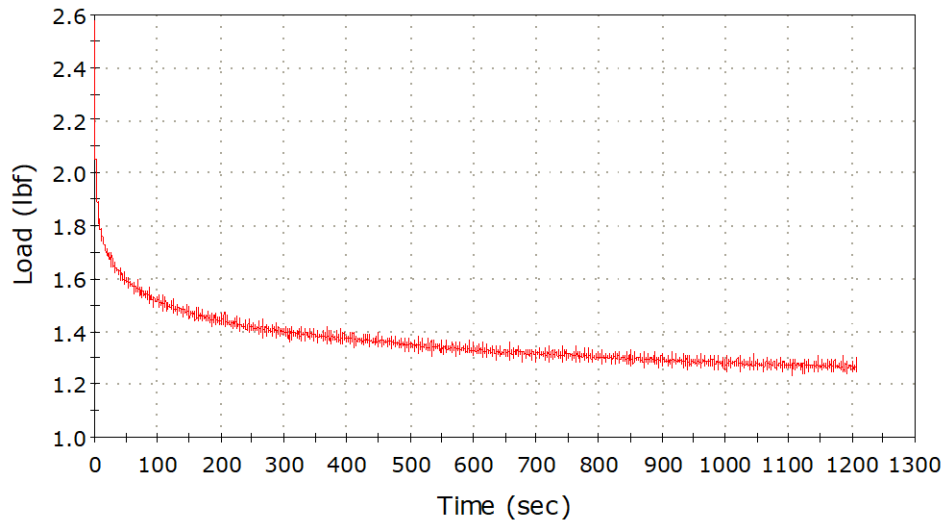




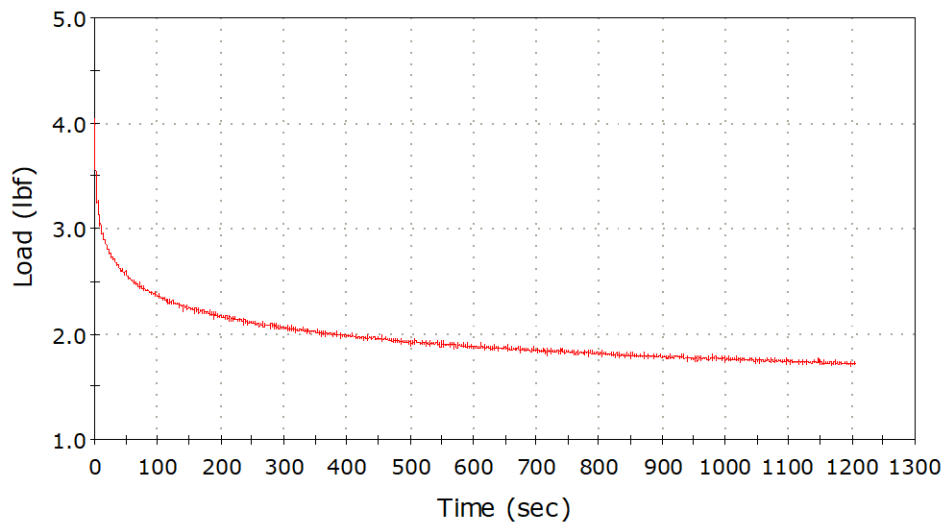


Appendix II. Stress relaxation curves for each sample

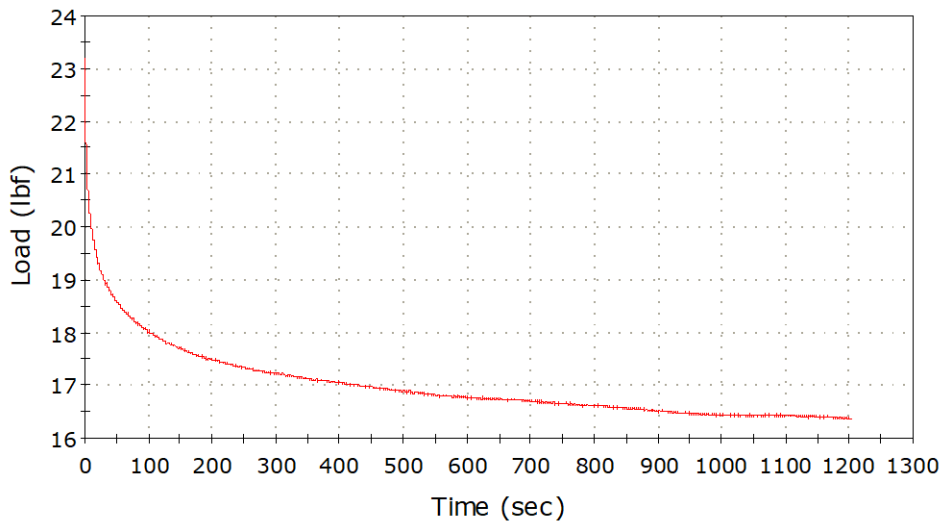
Band-Aid Johnson & Johnson Large Rolled Gauze



Equate Self-Adhering Sports Wrap

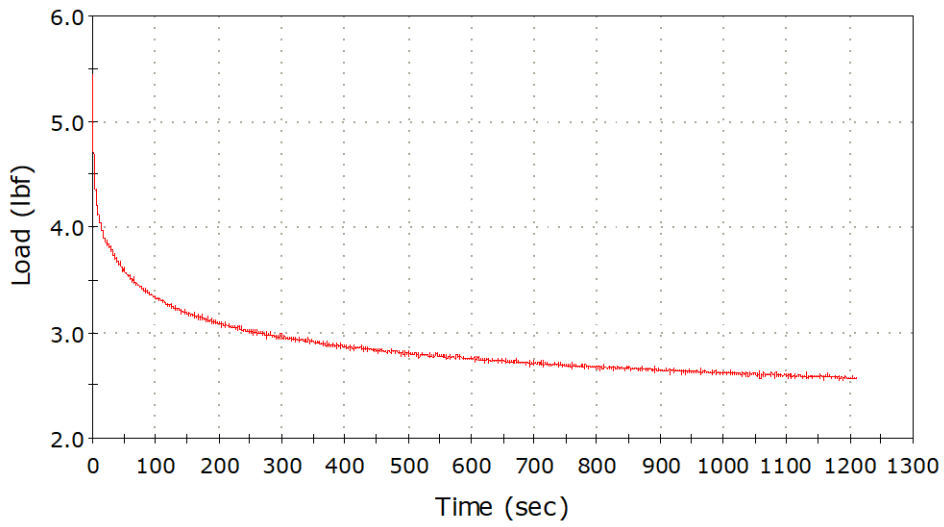


Mueller All-Purpose Support Wrap



Specimen #
1

Powerflex Self-Adhering Sports Wrap



Specimen #
1

Woven Non-Roll Elastic

